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Testing for reach-scale adjustments of hydraulic variables to soluble and insoluble strata: Buckeye Creek and Greenbrier River, West Virginia

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Abstract

An open question exists as to whether channel geometries and hydraulics are adjusted in bedrock streams with stable, concave profiles in a manner analogous to alluvial rivers. As a test of this problem, a comparison was undertaken of channel geometries and hydraulics among reaches with substrates that are of high mechanical resistance, but of variable chemical resistance. Reaches were selected from Buckeye Creek and Greenbrier River, West Virginia, USA because these streams flow over sandstones, limestones, and shales. The limestones have Selby rock resistance scores similar to those of the sandstones. A total of 13 reaches consisting of between 6 and 26 cross sections were surveyed in the streams. HEC-RAS was used to estimate unit stream power (ω) and shear stress (τ) for each reach. The reaches were selected to evaluate the null hypothesis that that ω and τ are equal atop soluble versus insoluble bedrock. Hypothesis tests consisted of paired *t*-tests and simultaneous, multiple comparisons. Geomorphic setting was included for Greenbrier River because previous studies have suggested that bedrock streams are intimately coupled with hillslopes. Holding geomorphic setting constant, three separate comparisons of ω and τ reveal that these variables are lowest atop soluble substrates in Greenbrier River (significance ≤ 0.05) and that changes in ω and τ are mediated by changes in channel geometry. Similarly, headwater reaches of Buckeye Creek developed atop shale and sandstone boulders are statistically distinguishable from downstream reaches wherein corrosion of limestone is the primary means of incision. However, comparisons in each stream reveal that channel geometries, ω and τ, are not strictly controlled by bed solubility. For constant substrate solubility along the Greenbrier River, ω and τ are consistently higher where a bedrock cutbank is present or coarse, insoluble sediment enters the channel. The latter is also associated with locally high values of ω and τ in Buckeye Creek. Assuming that incision by corrosion requires lower values of ω and τ because the channel need not be adjusted for block detachment and tool acceleration, we posit that the statistically lower values of ω and τ are tentative evidence in favor of differential geometric and hydraulic adjustments to substrate resistance. We observe that these adjustments are not made independent of geomorphic setting.

Keywords: Bedrock incision; Channel hydraulics; Karst; Fluvial processes

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1. Introduction

A small, but growing body of evidence suggests that bedrock streams can adjust longitudinal values of channel properties to the substrates being incised. Hydraulic or geometric adjustments have been posited based upon systematic, lengthwise changes in channel width atop uniform substrates (Montgomery and Gran, 2001), statistically meaningful correlations between channel form, substrate, and hydraulics (Wohl and Merritt, 2001), and higher values of erosion-associated hydraulic variables atop resistant strata among three streams in Japan (Wohl and Ikeda, 1998). These relationships imply that bedrock rivers may show longitudinal adjustments of hydraulic geometries similar to those known from alluvial rivers (Montgomery and Gran, 2001). However, substrate varies longitudinally in many bedrock streams and the erosional resistance of individual substrates can vary significantly because they include such variables as tensile strength, compressive strength, joint spacing, geologic structure, degree and type of cementation, Mohs hardness values of rock grains, and degree of weathering (Selby, 1980). Therefore, longitudinal changes in channel geometry may be nonsystematic in streams developed atop multiple substrates (Montgomery and Gran, 2001; Wohl and Achyuthan, 2002), which implies that geometric variables will not show simple power relationships to discharge as they do in alluvial streams (e.g., channel bed slope, width, and depth) (Montgomery and Gran, 2001). Instead, complex relationships probably exist such that mutual adjustments are made between bedrock channel geometry, hydraulics, and incision processes as discrete functions of substrate (Wohl and Merritt, 2001).

Bedrock streams may display stable, approximately concave profiles if geometric and hydraulic adjustments can be made such that incision rates are congruent in adjacent reaches developed atop different substrates (Pazzaglia et al., 1998). Therefore, an important test of whether bedrock streams display geometric and hydraulic adjustments is whether systematic, logical changes are found in these variables as functions of substrate type. For instance, shear stress (τ), unit stream power (ω), and mean cross section velocity ($\bar{u}$) should be lower atop less mechanically resistant substrates than resistant substrates because each hydraulic variable is associated with the tractive forces that detach blocks or abrade bedrock with tools (Baker and Pickup, 1987; Hancock et al., 1998; Wohl and Ikeda, 1998; Whipple et al., 2000a,b). However, mechanically resistant substrates can sustain steeper slopes for geologically significant periods of time and steeper slopes cause higher values of τ, ω, and $\bar{u}$ (Weissel and Seidl, 1998; Whipple et al., 2000b). Therefore, geometric and hydraulic adjustments cannot be recognized solely on the basis of correlations between the mechanical resistance of substrates and τ, ω, and $\bar{u}$.

The importance of variations in τ, ω, and $\bar{u}$ are the assumed relationships these variables have with actual incision processes, which are quarrying, abrasion, and corrosion. Observations indicate that bedrock channels are not significantly modified except during large, infrequent floods because thresholds of τ, ω, and $\bar{u}$ exist below which bedrock substrates cannot be mechanically eroded by floodwaters because either intact blocks are too large to be mobilized or tools, such as bed clasts, are not mobile (Hancock et al., 1998; Wohl, 1998; Whipple et al., 2000a). Locally, available discharge (Q), channel width (w), channel depth (h), and energy slope (S_e) determine τ, ω, and $\bar{u}$ as seen in the associated equations,

$$\bar{u} = \frac{Q}{A} \tag{1}$$

$$\tau = \gamma h S_e \tag{2}$$

$$\omega = \frac{\gamma Q S_e}{w} \tag{3}$$

where γ is the specific weight of water and A is channel cross section area (Bagnold, 1966; Howard, 1994, 1998). The bed slope (S_o) is often substituted for S_e because energy loss scales with S_o (Howard, 1994, 1998). Rapid $\bar{u}$ probably increases quarrying and abrasion capability in streams because high velocities and associated macroturbulence are associated with large instantaneous forces on the bed and rapid impact velocities of abrasive or concussive tools in floodwaters (Matthes, 1947; Baker, 1988; Hancock et al., 1998; Whipple et al., 2000a,b). Similarly, sufficiently high shear stresses can mobilize intact bedrock. In contrast, ω is complexly related to incision processes because the variable S_e subsumes a variety of other variables. However, concentration of power expenditure on the bed is enhanced by narrowing of the channel, which enhances quarrying and abrasion (Baker, 1988; Wohl, 1993).

Substrate determines the threshold values of τ, ω, and $\bar{u}$ required for mechanical incision because quarrying and abrasion are suppressed by large block sizes and hard substrates (Baker, 1988; O'Connor, 1993; Wohl, 1993; Hancock et al., 1998; Whipple et al., 2000a,b; Sklar and Dietrich, 2001). However, mechanical resistance is not the only measure of substrate resistance and other variables influence the ability of a stream to incise (Sklar and Dietrich, 2001; Wohl and Merritt, 2001). The resistance of substrate to corrosion is potentially important because carbonates are often found to occupy valley positions in humid settings despite moderate resistance to abrasion, high tensile strengths, and frequent occurrence as thick beds (Cardwell et al., 1968; White, 1988; Ford and Williams, 1989; Sklar and Dietrich, 2001).

The moderate to high mechanical resistance of carbonates, but low resistance to chemical attack, offers an opportunity to test for reach-scale adjustments of hydraulic variables to substrate because fundamental differences exist between corrosion and mechanical incision processes. Adjustments can potentially be sought by comparing channel geometry and hydraulics as functions of substrate solubility if we assume that an approximately concave profile represents an equilibrium state wherein incision rates are congruent atop diverse substrates (e.g., Pazzaglia et al., 1998). Hypothetically, the rate of mechanical energy expenditure (S_e) and, therefore, ω and τ should decrease where a stream is incising by corrosion, or the combined effects of mechanical and chemical erosion would cause excess erosion atop carbonates, which would be expressed as a gradient irregularity in the longitudinal profile of a river. This rationale is a direct extension of the hypothesis that reach-scale adjustments should exist between substrate resistance and channel hydraulics, but allows for direct testing of the hypothesis despite the co-dependence of mechanical substrate resistance and hydraulics. The hypothesis can only be tested where corrosion is a viable means of incision because mechanical incision may greatly outpace chemical incision in the majority of streams, particularly where incision rates are fast (Wohl, 1993; Hancock et al., 1998).

We investigate variations in geometry, hydraulics, and substrate in multiple reaches of two streams that are incising soluble and insoluble strata by quarrying, abrasion, and corrosion. We quantitatively explore whether ω and τ vary in concert with changes in channel substrate and geomorphic setting by examining multiple reaches in individual streams. The attendant data are used to tentatively evaluate the assumption that ω and τ are meaningfully related to substrate solubility. Therefore, our field-based investigation sheds important light on whether bedrock streams with stable, approximately concave profiles adjust their geometry and hydraulics to multiple substrates while maintaining smooth, concave profiles.

2. Research approach

2.1. Primary hypothesis and assumptions

We use intrastream comparisons of ω and τ to explore the influence of relative bed solubility on channel geometry and hydraulics in two bedrock streams incising soluble and insoluble strata. We employ surveying and modeling techniques developed in other rivers. These techniques presumably apply to Greenbrier River because the river is similar to the systems in which the techniques were developed (e.g., Baker and Pickup, 1987; Wohl, 1992, 1993; Wohl et al., 1994; Wohl and Merritt, 2001). The second stream, Buckeye Creek, drains a rugged, fluviokarst basin (Dasher and Balfour, 1994). Sequentially, the stream carries insoluble detritus from atop an escarpment, across a karst depression floor, and through a 1.6-km-long subterranean channel. All reaches in the cave are modeled as open-channel flow because passage sizes are large and a viable closed conduit model has yet to be developed for caves. We do not assume that large, cave-filling floods cannot generate larger values of ω and τ than we obtained from the open-channel models. Rather, we assume that the modeled open-channel flood provides a useful datum with which to begin a quantitative exploration of hydraulic adjustments in streams flowing across multiple substrates.

Using results from both streams, we test the null hypothesis that ω and τ are equal atop soluble versus insoluble bedrock for similar geomorphic settings. Separate comparisons of ω and τ are not supportive of one another because of their similar numerical origins and the relationship, $\omega = \bar{u}\tau$ (Eqs. (2) and (3)) (Bagnold, 1966). Similarly, $\bar{u}$ is not used separately in our statistical analyses because of its many direct and indirect influences on both ω and τ (Bagnold, 1966). We make these comparisons among reaches with carbonate-dominated valley walls because such comparisons should be more valid than comparisons among reaches with varied hillslope compositions.

We assume that statistical differences among reaches developed atop soluble versus insoluble strata are tentative evidence in favor of the research hypothesis that streams can adjust channel geometries and hydraulics such that incision is congruent in adjacent reaches being incised by quarrying, abrasion, or corrosion versus quarrying or abrasion without significant assistance by corrosion. The research hypothesis assumes that stream geometry is adjusted to generate higher values of ω and τ where incision is dominated by quarrying or abrading of insoluble strata rather than corrosion. Presumably, geometric adjustments could consist of decreasing the local bed slope, increasing width, or decreasing depth such that ω and τ are lower atop soluble bedrock among paired reaches. Notably, statistically significant results are not conclusive evidence in support of our research hypothesis because cause and effect cannot be shown using a field-based study alone. Also, we are not free to manipulate many potentially confounding variables. Our choice of large-scale variables (substrate and geomorphic setting) is guided by the assumption that the fundamental differences that exist between quarrying, abrasion, and corrosion may translate to statistically distinguishable values of ω and τ. A similar research hypothesis has been presented by Montgomery and Gran (2001), which states that adjustments in channel width can occur where substrates have different resistances such that τ is adjusted without changes in S_o.

The influence of geomorphic setting is partially evaluated for the Greenbrier River by examining ω and τ in the vicinity of bedrock cutbanks. We define bedrock cutbanks as unpaired, vertical bedrock faces extending 5 m or higher above the channel, which are opposed by unconsolidated bars, terraces, or colluvial deposits. The primary hypothesis is tested for soluble (no cutbank) versus soluble (cutbank), insoluble (no cutbank) versus insoluble (cutbank), and other combinations of the terms. These added tests allow us to crudely gage the influence of secondary variables on ω and τ.

The reach comparisons assume that incision rates are similar in the 13 stream segments we examine and that the distribution of hydraulic variables is related to substrate resistance and geomorphic setting because of long-term adjustments of channel geometry to substrate (e.g., cutbank versus no cutbank) (e.g., Miller, 1991; Howard, 1998; Wohl and Merritt, 2001). The latter assumption is invalid if the effects of base level fall or knickpoint migration dominate channel processes in either stream. Incision rates are approximately 40 m Ma^{-1} for all three streams (Dasher and Balfour, 1994; Springer et al., 1997; Shank and Sasowsky, 2001); therefore, we assume that the close proximity of reaches within each segment and lack of recognizable knickpoints between the reaches means that adjacent reaches are incising at similar rates. The stream segments are located in different longitudinal positions in the same large basin; no statistical comparisons are made between reaches in separate stream segments because of the possibility of asynchronous responses to base level fall or knickpoint propagation among the three segments.

2.2. Statistical tests

We obtain values of τ, ω, and $\bar{u}$ for 13 stream reaches of Buckeye Creek (eight reaches) and Greenbrier River (five reaches), WV by modeling floodwaters in surveyed reaches consisting of 6–26 cross sections. Reaches were chosen on the basis of substrate solubility, geomorphic setting, and accessibility. The program HEC-RAS, a one-dimensional, open-channel, step-backwater model, was used to generate values of τ, ω, and $\bar{u}$ (Hydrologic Engineering Center, 1998a,b). The null hypothesis is evaluated for Greenbrier River using Student's *t*-test comparisons of ω.

HEC-RAS results from Buckeye Creek are evaluated differently from those of the Greenbrier River. Statistical groupings of reach variables were made using the Student–Newman–Keuls (SNK) multiple comparison test ($\alpha = 0.05$). The SNK procedure was designed to identify means with no significant differences when a large number of comparisons are possible. The procedure is more conservative than making many *t*-test comparisons because many comparisons create ample opportunity for false declarations of significance due to experimental error or chance (Ott, 1992). The test is used here to determine if the headwater reach, which is incising shale, is statistically distinct from the reaches incising limestone. The five downstream-most reaches are in a cave, which is obviously related to corrosion processes. Therefore, the SNK procedure should distinguish those reaches from the headwater reach if the research hypothesis is plausible.

3. Study areas

3.1. Buckeye Creek

Buckeye Creek and Greenbrier River are incising Paleozoic sedimentary rocks in SE West Virginia, USA (Figs. 1 and 2). The smaller stream, Buckeye Creek, drains a 14-km^2, topographically enclosed

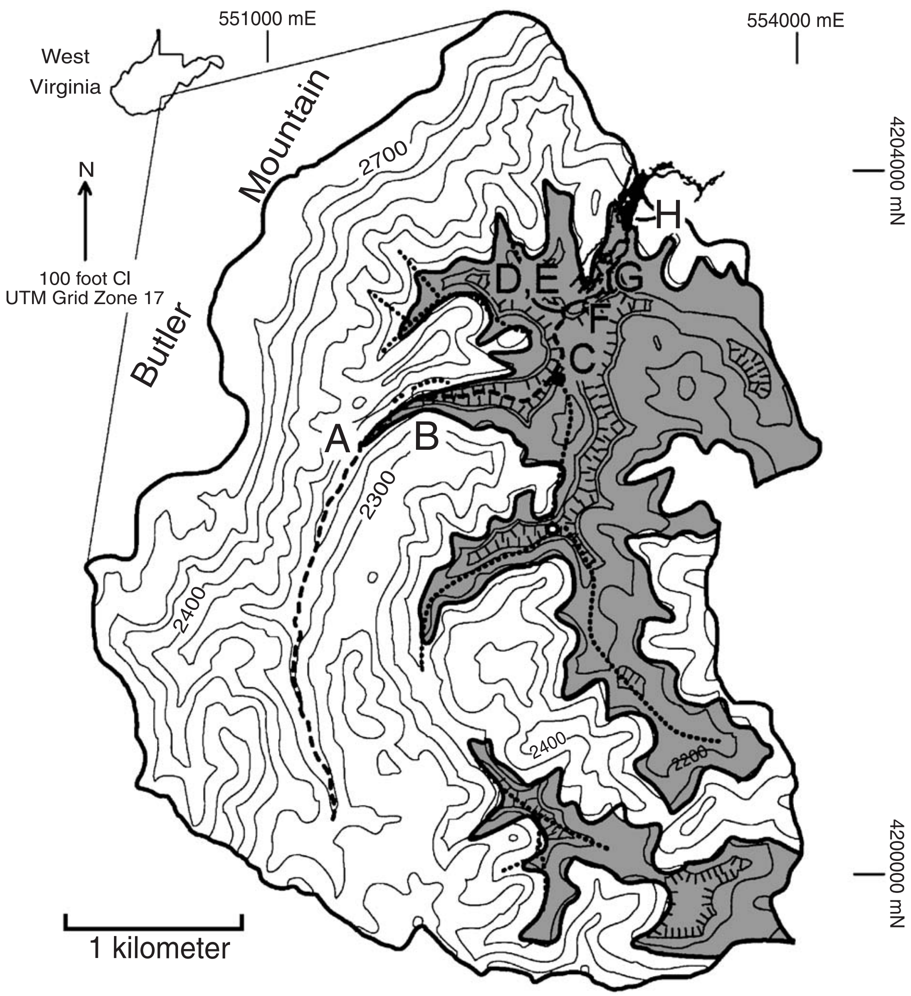

Fig. 1. Location and simplified geology map of the Buckeye Creek basin. Shading denotes Greenbrier Group limestones. White denotes Mauch Chunk clastics. Long dashes denote surface stream (Buckeye Creek), and short dashes denote subsurface flow routes. Letters denote reaches discussed in text. Geology and flow routes from Dasher and Balfour (1994).

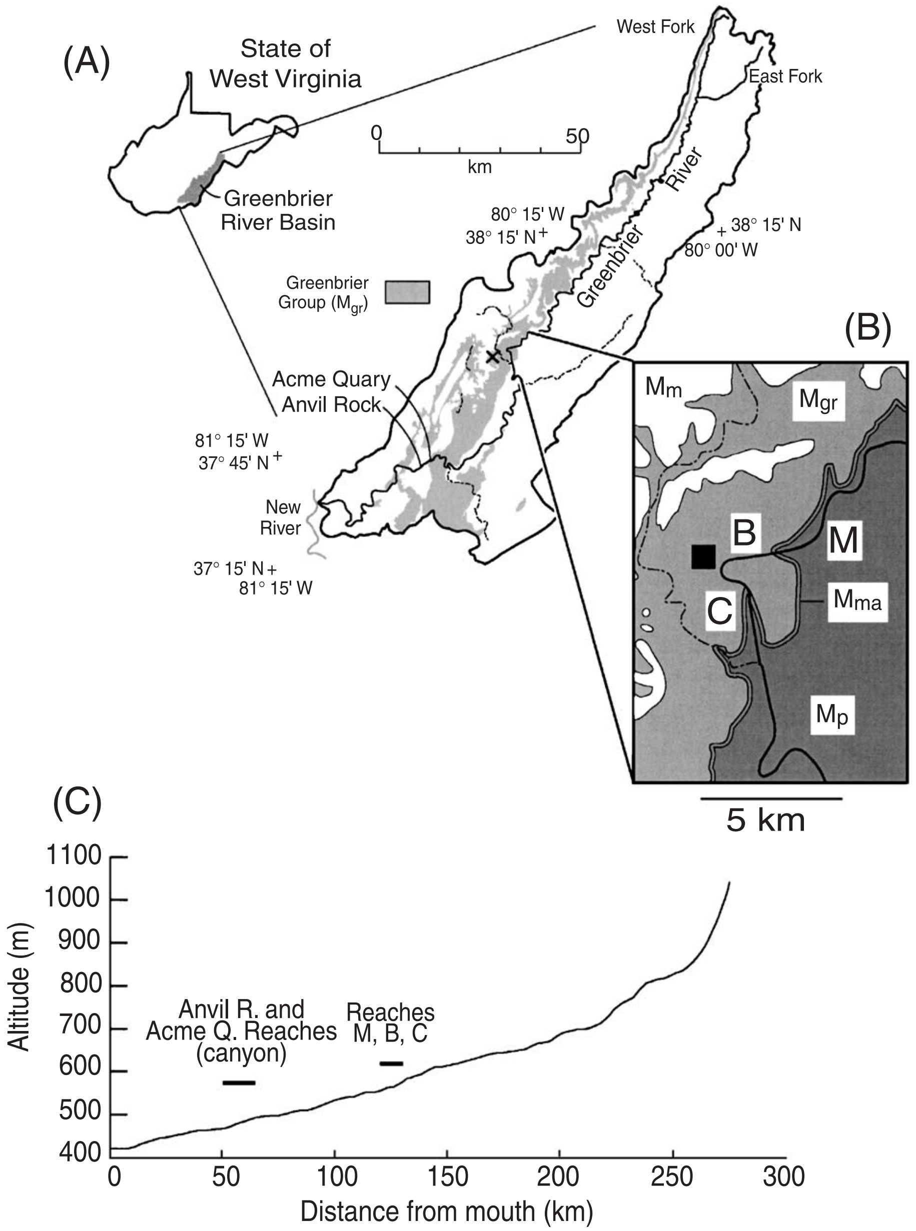

Fig. 2. (A) Locations of Greenbrier River catchment and study reaches. Large × identifies Buckeye Creek basin. (B) Detailed geologic map and location of Mile-27 (M), Bone Quarry (B), and Cathole (C) reaches. Maccrady Formation is denoted as Mma. Mm denotes Mauch Chunk sandstones and shales overlying carbonates of the Greenbrier Group (Mgr). Black rectangle identifies village of Renick. Geology from Cardwell et al. (1968). (C) Longitudinal profile of Greenbrier River with study reach locations.

fluviokarst basin near Renick, WV (Fig. 1). The basin lies on the eastern margin of the Appalachian Plateau physiographic province atop gently folded Mississippian sandstones, siltstones, and limestones. The limestones are medium to thickly bedded micrites and oolites, which are virtually pure calcite (McCue et al., 1939). Local climate is humid temperate with an average rainfall of 125 cm year^{-1}. Buckeye Creek exits the surface catchment through the Buckeye Creek Cave system and returns to the surface as springs on the banks of Spring Creek, which acts as a local base level (Dasher and Balfour, 1994; Jones, 1997). Passages in Buckeye Creek Cave average 8-m high and wide. The profile of Buckeye Creek is concave and the downstream profile has remained constant for the last 1 Ma (Dasher and Balfour, 1994). Karst features of the Buckeye Creek drainage basin and nearby portions of the Spring Creek valley are the subject of a monograph that also presents overviews of basin geology, geomorphology, and hydrology (Dasher and Balfour, 1994), which served as the basis for additional investigations summarized in Springer (2002a).

Eight reaches of Buckeye Creek were selected for study on the basis of substrate composition and longitudinal position (Table 1; Fig. 1). Study reaches include: three surface channels, four subterranean channels, and one channel extending from atop the karst depression floor to inside the cave. Sandstone boulders and cobbles supplied from upstream mantle the beds of reaches A and B (Table 1). Gravels dominate in downstream reaches except at the cave entrance where talus from the overlying cliff accumulates in the stream (Table 1; Fig. 1). Reach descriptions are provided in Table 1 and additional details can be obtained from Springer (2002a). The channel profile, as determined from paleochannels in Buckeye Creek Cave, has been stable for approximately 1 Ma, which implies that channel geometry is adjusted to substrate and valley wall interactions (Springer, 2002a). The chosen reaches have variable relationships to valley walls and sediment inputs (e.g., hollows), which undoubtedly causes differences in τ, ω, and $\bar{u}$. These differences have presumably been subsumed into channel geometry adjustments over the past 1 Ma. Therefore, interpretations of τ, ω, and $\bar{u}$ relative to long-term adjustment of channel processes to substrate for Buckeye Creek have some inherent and unquantified potential for error.

3.2. Greenbrier River

The larger stream, Greenbrier River, is a southward-flowing tributary of the New River with a drainage area of 3800 km^2 (Fig. 2). The catchment straddles the boundary between the Appalachian Plateau and Valley and Ridge physiographic provinces. The river principally flows along strike atop Paleozoic sandstones, siltstones, and shales. The river profile is approximately concave (Fig. 2). Five reaches with extensive bedrock exposure on the channel bed were selected from two segments of Greenbrier River (Fig. 2). Locally, the river is incising carbonates, which have higher compressive strengths than sandstones in the segments and similar Selby rock resistance scores (Table 2; Fig. 2). Basin climate is humid temperate. Mean annual precipitation declines downstream from a high of 152 cm year^{-1} in the western headwaters to a low of 100 cm year^{-1} at the river mouth (Jones, 1997).

Table 1
Buckeye Creek study reaches

Reach	Descriptors	Length (m)	Gradient (m m^{-1})	Cross sections	Bedrock or alluvial	Morphology	Bed lithology	Drainage area (km^2)	Selby rock resistance	Compressive strength[a]	d_{50} (ϕ)[a]
A	headwater	42.3	0.044	10	bedrock	cascade, run	shale	3.5	–	too soft[b]	– 7.2
B	upstream depression floor	53.0	0.029	12	alluvial	run	Ss clasts[c]	3.9	–	–	– 7.2
C	depression floor	75.3	0.005	9	alluvial	pool-riffle	Ss clasts[c]	10.4	–	–	– 5.0
D	depression floor; cave entrance	142.4	0.016	26	mixed	pool-riffle	limestone	10.4	78	64 ± 2	– 7.2
E	cave	118.9	0.009	17	bedrock	cascade, pool-riffle	limestone	13.4	76	64 ± 2	– 4.6
F	narrow canyon	65.1	0.003	20	bedrock	forced pool	limestone	13.4	88	65 ± 2	– 3.7
G	large, tubular	77.0	0.004	12	bedrock	pool-riffle	limestone	13.4	66	67 ± 2	– 3.5
H	large canyon	99.8	0.000	15	alluvial	pool-riffle	limestone[c]	13.4	66	69 ± 2	– 3.6

[a] Mean ± 1 S.D. Minimum n for compressive strength is 10. Minimum n for Wolman count d_{50} is 100.
[b] Surface of massive shale is too soft for safe use of measurement device.
[c] Ss denotes sandstone. Limestone underlies alluvium at an undetermined depth.

Table 2
Greenbrier River study reaches

Reach	Length (m)	Gradient ($m\ m^{-1}$)	Cross sections[a]	Bed lithology (s)	Valley wall lithology (s)	Selby rock resistance	Compressive strength[b]	d_{50} (ϕ)[b,c]	Ls Fract. (%)[d]
Anvil Rock	860	0.002	7 (3)	limestone	limestone	95	59.7 ± 3.2	− 7.94 ± 1.03	8.00
Acme Quarry	780	0.002	7 (3)	limestone	clastics + Ls	92	65.7 ± 1.6	− 7.86 ± 0.88	10.7
Mile-27	640	0.001	6 (3)	sandstone	Ls + clastics	80	49.8 ± 1.1	− 7.50 ± 1.14	0.01
Bone Quarry	720	0.002	8 (4)	limestone	limestone	77	59.3 ± 2.9	− 7.30 ± 0.81	0.67
Cathole	1450	0.000[e]	4 (2)	limestone	limestone	86	59.3 ± 2.9	− 7.95 ± 0.86	4.33
			2 (0)	shale		34	too soft[f]		
			6 (2)	sandstone		77	55.1 ± 2.8		

[a] Total number of cross sections with number of riffles in parentheses.
[b] Mean ± 1 S.D. of compressive strength. Minimum n for each lithology is 10.
[c] Wolman counts from atop riffles, except at Anvil Rock where counts are from a bar. Minimum n is 100.
[d] Percent of bed clasts composed of limestone (minimum n is 100).
[e] Calculated gradient is 0.0003, but rounding yields a value of 0.000 because of averaging across a 1-km-long pool.
[f] Friable shale is too soft and fractured for safe use of measurement device.

Five reaches of the Greenbrier River were chosen for study (Table 2; Fig. 2). The Greenbrier River is a perennial, unregulated bedrock stream with an overall stream gradient of 0.001 m m^{-1} (Fig. 2). Riffles, underlain by cobbles and fine boulders, alternate with mixed bedrock- and cobble-floored pools, except at Anvil Rock. Mass wasting processes on adjacent valley walls deliver sandstone boulders, commonly 3 m along the a-axis, to the Anvil Rock reach. Potholes up to a meter wide are developed in the boulders. Reach descriptions are provided in Table 2 and additional details can be found in Springer (2002a). The overall river profile is concave but displays local concavities and convexities (Fig. 2). The three upstream reaches were chosen from a location where the longitudinal profile is unbroken and the stream flows over three different substrates over a relatively short distance (shale, sandstone, and limestone) (Fig. 2). Using the Selby index of rock hardness (Selby, 1980), the mechanical resistance of the limestones are similar to the sandstones (Table 2). These similarities stem from thick bedding, sparse joints, and high compressive strengths among the limestones. The close proximity of the three substrates allows paired t-tests to be performed as functions of relative substrate solubility. Preplanned comparisons meant that reaches were selected where the river is flowing atop limestone and sandstone away from the valley wall (Bone Quarry versus Mile-27) and limestone and sandstone, but beneath a cutbank (Cathole). The influence of an additional confounding variable was evaluated by selected two reaches that lie in close proximity, but which do and do not receive coarse, insoluble sediment from the valley wall (Acme Quarry versus Anvil Rock). As with other field studies, the sites for preplanned comparisons of reach processes were not randomly selected from all available sites because not all sites were freely accessible and additional variables would need to have been considered (e.g., Wohl and Ikeda, 1998; Wohl and Merritt, 2001; Whipple et al., 2000b).

4. Methods

4.1. Channel geometry

The hypothesis being tested requires comparison of channel hydraulics as a function of relative substrate solubility (soluble versus insoluble). Channel geometry largely controls hydraulics (Hydrologic Engineering Center, 1998b); therefore, the hypothesis is a simplified test for geometric adjustment. Evaluation of the relationships between channel geometry, substrate, hydraulics, and incision processes requires quantitative data from all three categories. Geometric data was obtained by using a TopCon total station with a laser EDM (12 reaches) and a TopCon transit and stadia rod (reach C in Buckeye Creek). Cross sections were surveyed atop riffles and in intervening pools. Cross sections were spaced approximately evenly if pool-riffle morphology was not present (reaches A and B in Buckeye Creek). Ceiling heights were obtained in reaches of Buckeye Creek Cave using a stadia rod. These heights were used to confirm that flow depth estimates produced during open-channel modeling did not exceed ceiling heights.

4.2. Substrate

The channel bed and substrate were characterized for all reaches by performing Selby rock hardness tests and measuring bed grain sizes using sieving and Wolman pebble counts (Tables 1 and 2) (Wolman, 1954; Selby, 1980). Selby rock hardness scores are provided in Tables 1 and 2. Scoring is based upon the compressive strength of the bedrock, as measured with a Schmidt rock hammer, joint spacing, structure, weathering, and groundwater outflow (Selby, 1980). More resistant rocks have higher Selby scores. Notably, Selby scores do not account for the chemical resistance of the substrate being examined.

Bed grain sizes on channel surfaces were sought as independent tests of whether open-channel modeling of flow in Buckeye Creek is reasonable. Specifically, the longitudinal distribution of τ generated by HEC-RAS should be similar to the distribution of grain sizes on the bed because τ is intimately associated with bed load transport. Such a test is particularly necessary because flow in Buckeye Creek Cave is modeled as open-channel flow. Wolman counts were used everywhere that grain sizes were too large for mechanical sieving (coarser than $-4\ \phi$). Sieves were spaced from every 0.5 or 1 ϕ from 0 to $-4\ \phi$ for bagged samples. Values of d_{16}, d_{50}, and d_{84} were graphically estimated for sieved sediments and ordering of the 100 sizes obtained for each Wolman count (Wolman, 1954).

4.3. Hydraulics

All 13 stream reaches examined were modeled using HEC-RAS, a one-dimensional, open-channel, step-backwater model (Hydrologic Engineering Center, 1998a,b). HEC-RAS is widely used for field-based studies of channelized flow in bedrock streams (e.g., Wohl, 1992, 1993; Wohl and Ikeda, 1998; Wohl and Merritt, 2001). Estimates of ω, τ, and $\bar{u}$ in the channel were obtained for open-channel reaches directly from HEC-RAS. The normal depth was assumed to describe downstream boundary conditions, except for reach D, the cave entrance where initial model runs yielded critical flow. Subcritical flow has been observed in reach D during large floods (Springer, 2002a); therefore, the downstream water surface elevation was raised from the normal depth until subcritical flow prevailed throughout the reach.

Representative discharges are necessary for hydraulic models of flooding in bedrock rivers. The 100-year flood has been used in some studies for which gaging records are available, but paleodischarges are commonly recovered by matching computed water-surface profiles to the highest available paleostage indicators (e.g., O'Connor, 1993; Wohl et al., 1999). Flood magnitudes with longer return periods may be more important than the 100-year flood for channel incision, but existing gaging data do not allow reliable calculation of the magnitude of larger floods (e.g., 500-year flood). Therefore, we chose to use the 100-year flood in the five Greenbrier River reaches. Discharges were estimated using gage records and the flood recurrence analysis program EMA (England, 1999). A 71-year record of annual peak discharges is available for the Renick reaches using U.S. Geological Survey (USGS) gage #03182500 at Buckeye, WV. A 105-year record of annual peak discharges is available for the canyon reaches using USGS stream gage #03183500 at Alderson, WV. Using EMA, the 100-year flood at the Buckeye gage is estimated as 1763 $m^3\ s^{-1}$, and the 100-year flood at Alderson is estimated as 2254 $m^3\ s^{-1}$. A roughness value was calculated for the Acme Quarry reach using a paleostage indicator (PSI) and known discharge for the flood of record (Springer, 2002b). This roughness value, $n = 0.041$, was used throughout all other reaches of the Greenbrier River except for the Anvil Rock reach where a value of 0.051 was used because of a narrower channel and prevalence of boulders exceeding several meters in all dimensions throughout the reach.

Buckeye Creek is ungaged and no useful high water marks were observed along the surface channel. Conduit flow or condensation has overprinted or eroded open-channel PSIs in most of Buckeye Creek Cave. Therefore, paleodischarge was estimated using scallops, which are geometrical arrangements of asymmetrical concavities formed by corrosion and abrasion of channel margins. The population statistics of scallops are discretely related to cave passage sizes and some formative discharge (Blumberg and Curl, 1974; Pisarowicz and Maslyn, 1981; Lauritzen et al., 1985; Lauritzen and Lundberg, 2000). Using scallops, Springer and Wohl (2002) report that 9.5 m^3 s^{-1} is representative of the upper flood regime in Buckeye Creek Cave.

The model discharge used for open-channel flow in the cave is 9.4 m^3 s^{-1}, which is the maximum discharge for which open-channel flow prevails in the cave. We assume that using the largest possible discharge potentially associated with open-channel flow provides an upper limit on ω and τ generated by open-channel flow in the cave. However, discharge changes rapidly in headwater catchments (Smith et al., 1996). As a result use of the calculated paleodischarge estimate throughout the 14-km^2 basin is inappropriate. Therefore, an instantaneous runoff value of 0.7 m^3 km^{-1} s^{-1} calculated using basin area and discharge in the cave was multiplied by catchment area of each reach to yield an appropriate model discharge (Table 3). Instantaneous runoff production rates generally increase headward, so the calculated value is probably low for headwater channels (Smith et al., 1996), but the value represents a high-magnitude, low-recurrence interval flood because of the association of scallops with low-frequency floods (Lauritzen et al., 1985; Lauritzen and Lundberg, 2000). Such floods are generally assumed to be the most effective agents of channel erosion in bedrock streams and caves (Lauritzen et al., 1985; Baker, 1988; Palmer, 1991).

4.4. Declaration of incision processes

Evidence of incision mechanisms was sought during data collection in all bedrock reaches examined in Buckeye Creek and Greenbrier River. Mechanically driven incision processes, such as quarrying and abrasion, occur during floods, which prevent direct observation of bed erosion. As a result, quarrying and abrasion are recognized on the basis of erosion features in channels rather than by direct observation of incision phenomena (e.g., Wohl, 1992, 1993; Hancock et al., 1998; Whipple et al., 2000a,b). Quarrying was identified on the basis of step-like ledges with missing and detached blocks. Abrasion was identified by the presence of potholes with grinders and other sculpted forms (Wohl, 1993; Hancock et al., 1998). Corrosion was identified by the presence of scallops and corrosion tubes in soluble strata (Blumberg and Curl, 1974; White, 1988; Springer et al., 1997). Many sculpted forms can be created by abrasion and corrosion, so anastomose tubes and corrosion pitting were especially valuable evidence of corrosion (Springer, 2002a). Using these criteria, the principle incision mechanisms in each reach were qualitatively identified. Corrosion was evident in all limestone reaches. Quarrying is enhanced at Acme Quarry by corrosion widening of block-bounding joints. Evidence of abrasion was only observed at Anvil Rock in Greenbrier River and reach B in Buckeye Creek. Abrasion is especially evident where large boulders constrict the channel at Anvil Rock. Sandstone boulders display potholes up to 1 m in

Table 3
Incision processes and HEC-RAS results for Buckeye Creek

Reach	Model discharge (m^3 s^{-1})	Bed lithology	Alluvial, bedrock, or mixed	Incision processes[a]	Average cross section values		
					ω (W m^{-2})[b]	τ (N m^{-2})[b]	$\bar{u}$ (m s^{-1})[b]
A	2.4	shale	bedrock	Q	190 ± 180	95 ± 73	1.6 ± 0.6
B	2.7	limestone	alluvial	Ab[c]	150 ± 40	90 ± 18	1.6 ± 0.1
C	7.3	limestone	alluvial	n/a	35 ± 21	30 ± 11	1.1 ± 0.2
D	9.4	limestone	mixed	Q, C	81 ± 150	40 ± 51	1.2 ± 0.7
E	9.4	limestone	bedrock	C	60 ± 83	28 ± 26	1.6 ± 0.7
F	9.4	limestone	bedrock	C	6 ± 3	8 ± 3	0.6 ± 0.1
G	9.4	limestone	bedrock	C	34 ± 23	22 ± 10	1.4 ± 0.3
H	9.4	limestone	alluvial	n/a[d]	43 ± 31	26 ± 12	1.5 ± 0.4

[a] Ab denotes abrasion; P denotes plucking; Q denotes quarrying; C denotes corrosion. Order reflects inferred relative roles.
[b] Mean ± 1 S.D.
[c] Abrasion is diminishing sandstone boulders atop an alluvial bed.
[d] Evidence of corrosion is found on bedrock banks, but there are no bedrock bed exposures.

diameter, flutes on upstream faces, and complex sculpted forms on downstream faces.

5. Results

5.1. Buckeye Creek

5.1.1. Substrate, hydraulics, and incision processes

Values of ω and τ are highest atop the shale and decline markedly in the downstream direction as Buckeye Creek flows toward and through Buckeye Creek Cave (Table 3; Fig. 3). Grain size, ω, and τ are highest in reaches A and B (Fig. 3). Grain size declines as the stream flows across the depression floor but abruptly increases at the entrance constriction, reach D, where the bed gradient briefly increases and coarse talus enters the channel from an overlying cliff (Table 1). Changes in median grain size mirror changes in ω and τ (Fig. 3). The similar trends of the independently estimated grain sizes and model values are reassuring because grain size typically varies with

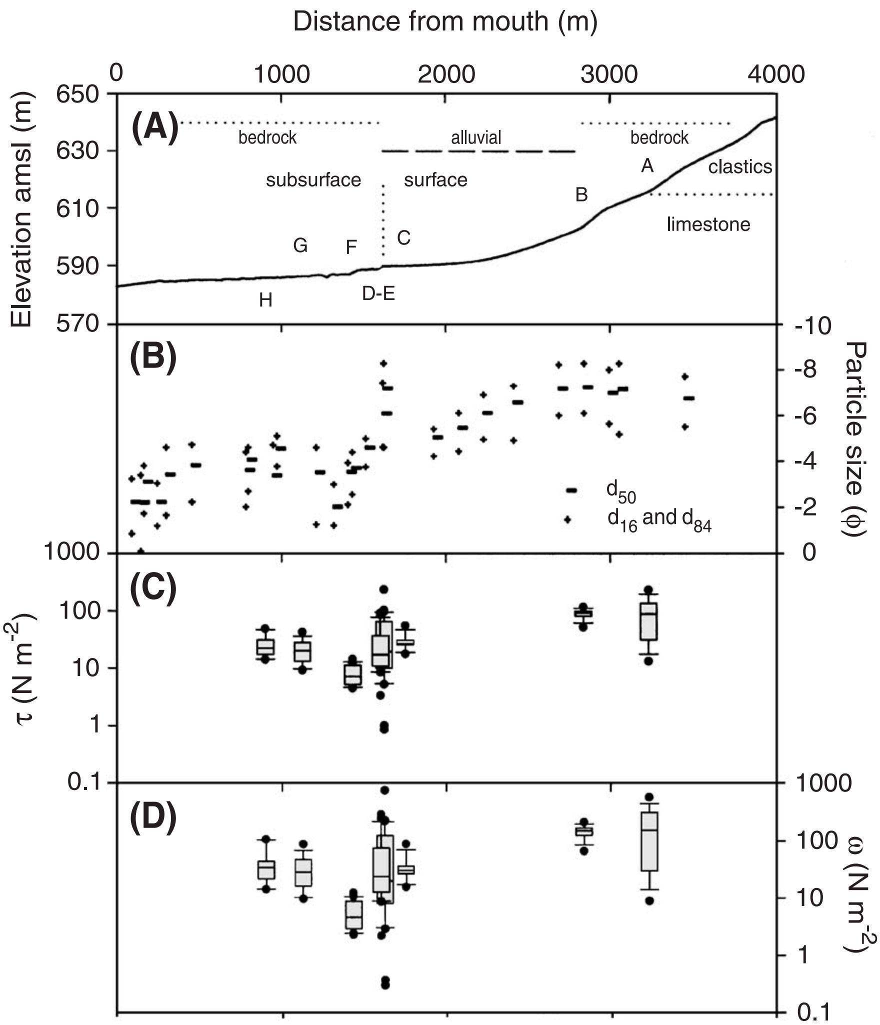

Fig. 3. Longitudinal distribution of modeled variables and grain size in Buckeye Creek. (A) Longitudinal profile with reach locations identified by letters and reach classifications noted. (B) Mean clast sizes along stream as determined using Wolman counts and sieving. (C) Box plot of shear stress (τ) values. (D) Box plot of unit stream power (ω). Note log scale of y-axes in plots C and D.

stream competence, which is complexly related to S_e and $\bar{u}$ in bedrock streams (Eqs. (2) and (3); Fig. 3) (Bagnold, 1966; Baker and Pickup, 1987; O'Connor, 1993). Although this does not constitute a postori validation of our assumption(s), the results do not contradict our assumption that the open-channel data are useful for interpreting channel processes in Buckeye Creek Cave.

The changes in ω and τ occur in concert with changes in perceived modes of incision. Quarrying is evident in reach A, as determined by the presence of shale blocks detached from the channel bed (e.g., Tooth et al., 2002). Abrasion of a resistant substrate is evident in reach B, as determined by the presence of potholes on small sandstone boulders in the channel and smoothing of boulder faces (e.g., Wohl, 1993). The implication is that ω and τ are lowest where the stream is reasonably expected to be incising by corrosion, such as in Buckeye Creek Cave, and higher where the channel is incising by quarrying and abrading coarse, insoluble sediment shed by the overlying escarpment (reaches A and B). Separate from the cave, evidence of corrosion is abundant in the downstream reaches. Banks contain solution cavities, projections on passage walls are smoothed, and sculpted forms attributable to corrosive attack are sometimes so numerous as to cover all channel surfaces (Springer and Wohl, 2002).

The SNK procedure distinguishes ω and τ in reaches A and B from those in the cave, which means that the null hypothesis of difference as a function of substrate cannot be accepted. Notably, values are approximately an order of magnitude different in portions of the cave from values in reaches A and B (Table 3; Fig. 4). These large differences are presumably not entirely attributable to geometric and hydraulic adjustments to substrate, but probably include the added effects of differences in geomorphic setting. The results do run contrary to the expectation that stream power, which is $\gamma Q S_e$, should increase as discharge increases quickly along the length of headwater catchment (Knighton, 1999). Recognizing that stream confinement increases as the stream enters the cave, we would reasonably expect that ω should increase as well (Eq. (3)). However, ω and τ decline because S_e declines as S_o lowers and channel width actually increases in the cave,

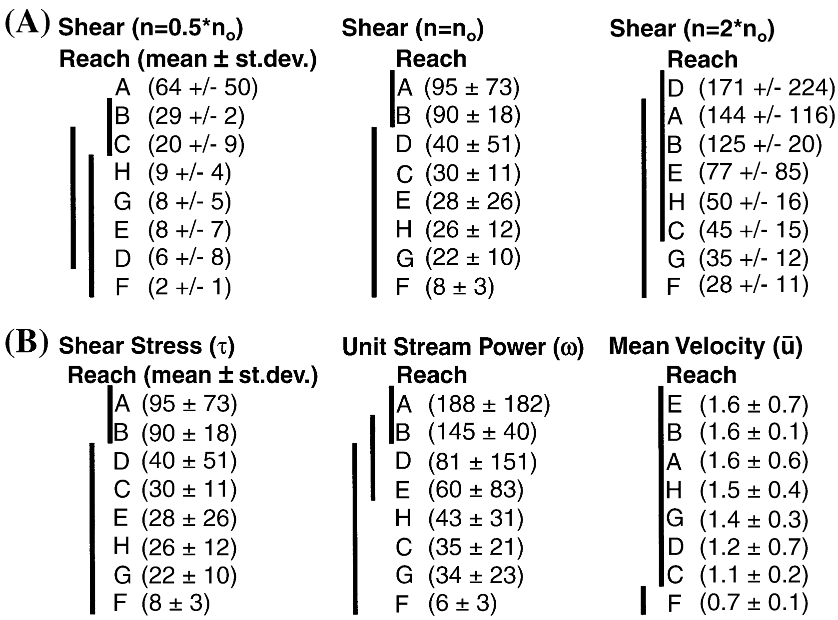

Fig. 4. (A) Comparisons of mean shear stress between reaches as classified using the Student–Newman–Keuls (SNK) multiple-comparison method for different values of Manning's n (Ott, 1992). (B) Comparisons of selected variables between reaches as classified using the Student–Newman–Keuls (SNK) multiple-comparison method for visually estimated values of Manning's n (Ott, 1992).

possibly because of a lack of bank vegetation to simultaneously bind and trap sediment.

5.1.2. Sensitivity to Manning's n

The effect of visually choosing Manning's n must be addressed because channelized flow has received virtually no quantitative treatment in caves. Sensitivity analyses were performed on the visually estimated roughness value (n_o) by performing model runs with roughness values that were 50% and 200% of n_o. The sensitivity of model output to different roughness values can be assessed by comparing statistical groupings of the reaches as functions of roughness values (Fig. 4A). All three model runs produce high τ for surface and entrance reaches, but two of the three SNK analyses distinguish between surface, cave entrance, and distal cave segments. Fewer significant differences are recognized among the cave and surface reaches for the $n=2n_o$ data, but groupings preserve the trend seen in the other two; low-gradient passages downstream of reach D yield low τ and group separately from surface segments and those near the cave entrance (Tables 1 and 3; Fig. 4A).

5.2. Greenbrier River

Values of ω and τ span an order of magnitude atop limestone substrates in the Greenbrier River (Table 4). Values are lowest at Bone Quarry atop a soluble substrate and highest at the downstream terminus of the Cathole reach where the river is incising sparsely jointed, quartz sandstone (Table 4; Fig. 2). The river is incising two other substrates in the 1.4-km-long Cathole reach and ω and τ are lowest in the Cathole reach atop an insoluble shale of the Maccrady Formation (Table 4). Flow geometry is an important control on changes in ω and τ in bedrock streams because of their dependence upon depth and energy loss (Eqs. (2) and (3)) (Baker and Pickup, 1987; Wohl, 1992, 1993; O'Connor, 1993). Notably, top width is least where the river is incising massive sandstone (Cathole) and choked with sandstone boulders (Anvil Rock) (Table 4). Previous studies have noted similar associations of resistant substrates or boulder deposits with narrow channels (Wohl, 1992, 1993; Baker and Pickup, 1987; Wohl and Ikeda, 1998). Theoretically, channel narrowing represents a geometrical adjustment whereby high ω, τ, and $\bar{u}$ increase mechanical incision capability such that incision is congruent with adjacent reaches with lesser substrate resistance or hillslope interactions (e.g., Montgomery and Gran, 2001).

The Greenbrier River is incising by quarrying, abrasion, and corrosion in the five reaches examined, as determined from visible evidence (Table 4). Locally derived, largely unmodified blocks of sandstone were observed on the river bed in the Mile-27 and Cathole reaches. Similarly, limestone blocks were observed to be detached from the channel bed and to comprise nontrivial fractions of the bed load in all but the Bone Quarry and Mile-27 reaches (Table 2). The two exceptions are notable. The Mile-27 reach is incising sandstone and limestone is not found in the

Table 4
Incision processes and HEC-RAS results for Greenbrier River

Reach	Model discharge ($m^3\ s^{-1}$)	Bed lithology[a]	Bedrock cutbank?	Incision processes[b]	Mean depth (m)	Average cross section values: Mean top width (m)	ω ($W\ m^{-2}$)[c]	τ ($N\ m^{-2}$)[c]	$\bar{u}$ ($m\ s^{-1}$)[c]
Anvil Rock	2300	Ls	yes	Ab + Q + C	8.5	80	720 ± 170	170 ± 27	4.3 ± 0.4
Acme Quarry	2300	Ls	yes	C + Q	7.4	111	400 ± 190	120 ± 35	3.3 ± 0.7
Mile-27	1800	Ss	yes	Q	5.0	148	250 ± 83	87 ± 19	2.8 ± 0.3
Bone Quarry	1800	Ls	no	C	9.5	131	41 ± 18	25 ± 7	1.6 ± 0.3
Cathole	1800	Ls	yes	C + Q	5.4	110	410 ± 130	110 ± 23	3.5 ± 0.4
		shale	partial	Q	6.0	116	180 ± 73	62 ± 18	2.8 ± 0.4
		Ss	yes	Q	4.7	103	880 ± 66	200 ± 11	4.4 ± 0.1

[a] Ls denotes limestone; Ss denotes sandstone.
[b] Ab denotes abrasion; Q denotes quarrying; C denotes corrosion. Order reflects inferred relative roles.
[c] Mean ± 1 S.D. from atop riffles, except for shale values at Cathole. Shale only outcrops in pool.

channel upstream of this reach, whereas the Bone Quarry reach is incising limestone. The small fraction of limestone clasts on the bed at Bone Quarry, absence of quarried surfaces, and abundant evidence of corrosion including anastomose tubes and solution pits suggests that the bed is primarily being incised by corrosion together with abrasion by tools (clasts) mobilized during floods. Top width increases dramatically at Bone Quarry, which decreases ω and effectively decreases τ by influencing depth (Eqs. (2) and (3)). Elsewhere, the river is incising limestones by various combinations of quarrying, abrasion, and corrosion. The precise contributions of each incision mechanism are impossible to quantify, but the relative amounts of visual evidence for each mechanism were noted in the field and used to crudely determine their relative importance (Table 4).

The preplanned *t*-test comparisons are instructive (Table 5). The three comparisons of limestone versus sandstone substrate are statistically significant where the comparisons are made for common geomorphic setting (comparisons 1, 2, and 4). However, limestone-floored reaches are also statistically distinct from one another where only one reach is strongly influenced by either a bedrock cutbank or boulder-sized, insoluble detritus supplied by the valley wall (comparisons 5 and 6). This outcome is not surprising because various authors have speculated that hillslopes and bedrock streams must mutually influence one another (e.g., Burbank et al., 1996; Weissel and Seidl, 1998). The effect of such interactions can be seen in the outcome of comparison 3, which is the only nonsignificant comparison. Unit stream power is higher where the river is incising limestone beneath a bedrock cutbank, which supplies coarse boulders to the stream, and lower where the river is incising sandstone away from the valley wall. By implication, the simplified notion that bedrock stream geometries and, hence, hydraulics are adjusted to substrates is only applicable where reaches have similar geomorphic settings because large-scale variables, such as hillslope interaction, are likely to overwhelm the effects of substrate. This has also been posited on the basis of disagreements between theoretical models and longitudinal river profiles (e.g., Snyder et al., 2000).

6. Discussion

Previous studies have found positive associations between resistant strata and hydraulics variables such as ω and τ (Baker and Pickup, 1987; Wohl, 1992, 1993; Wohl and Ikeda, 1998). These studies did not use paired reaches in individual streams to attempt to recognize geometric or hydraulic adjustments, although Montgomery and Gran (2001) did use lengthwise measurements of channel width to suggest that hydraulic geometries scale with basin area in bedrock streams incising homogenous substrates. In this study, values of ω and τ are lowest atop soluble substrates versus insoluble substrates for both paired and multiple comparisons (Table 5; Fig. 3). Assuming that corrosion reduces the need for mechanical energy expenditure in a stream, the simplest interpretation of these outcomes is that the examined streams have adjusted channel geometries and hydraulics such that incision is congruent in adjacent reaches that are being incised by quarrying, abrasion, or corrosion versus quarrying or abrasion without significant corrosion.

Table 5
Results of hypothesis tests for unit stream power (ω)

Comparison	Reaches compared	Substrate comparison[a,b]	Geomorphic setting comparison[a,b]	*t*-statistic (significance)	Hypothesis test outcome
1	Bone Quarry vs. Mile-27	Ls vs. Ss	no cutbank vs. no cutbank	4.3 (0.05)	cannot accept
2	Cathole (Ls) vs. Cathole (Ss)	Ls vs. Ss	cutbank vs. cutbank	4.8 (0.02)	cannot accept
3	Cathole (Ls) vs. Mile-27	Ls vs. Ss	cutbank vs. no cutbank	1.8 (0.15)	fail to reject
4	Bone Quarry vs. Cathole (Ss)	Ls vs. Ss	no cutbank vs. cutbank	17.7 (0.03)	cannot accept
5	Bone Quarry vs. Cathole (Ls)	Ls vs. Ls	cutbank vs. no cutbank	5.0 (0.04)	cannot accept
6	Anvil Rock vs. Acme Quarry	Ls vs. Ls	Ss boulders vs. no Ss boulders	2.7 (0.04)	cannot accept

[a] Ls denotes limestone; Ss denotes sandstone.
[b] Variables are ordered respective to ordering of reaches in second column.

The association of ω and τ with particular substrates reflects variations in channel geometry in Greenbrier River. Channel widths are narrowest atop sandstone and where sandstone boulders clog the channel (Cathole and Anvil Rock) (Table 4). Channel width is greatest at Bone Quarry, which is consistent with the notion that channel incision is largely being accomplished by corrosion because large channel widths increase the amount of corrosive floodwaters in contact with the bed for a fixed quantity of water. Among paired reaches with the same substrate, channel widths are narrowest for the reach beneath a bedrock cutbank or receiving coarse, insoluble sediment (Tables 4 and 5). This is consistent with the notion that hillslope interactions materially influence bedrock channel processes (Howard, 1998; Snyder et al., 2000). The role of such confounding influences is difficult to discern in Buckeye Creek because of the diverse geomorphic settings of the study reaches, although an increase in ω and τ at the cave entrance is the result of an overlying cliff supplying coarse sediment to the channel. The lowest values of ω and τ are found in the cave, which is arguably the result of channel geometry and hydraulics being adjusted for incision by corrosion, which presumably does not require high values of ω and τ.

The effect of local differences in hillslope interactions is that the occurrences of quarrying, abrasion, and corrosion are not strictly controlled by relative bed solubility in either stream. Abrasion predominates in reach B of Buckeye Creek where coarse sandstone boulders are deposited and stored at the upstream terminus of the karst depression (Table 1). Similarly, abrasion is important atop sandstone boulders mantling the limestone bed at Anvil Rock in Greenbrier River. Coarse, insoluble sediment shields the bed at each location from corrosion and therefore must be diminished or mobilized if incision is to be maintained over geologic time, evidently because interstitial waters are ineffective at bedrock incision (e.g., White, 1988; Ford and Williams, 1989). The inputs of insoluble sediment are permanent features of the landscape, so the unbroken profiles seen in Figs. 1 and 2 imply that the channels and hillslopes have adjusted to maintain congruous incision in all reaches despite differences in substrate and sediment inputs. The implication is that soluble strata will rarely be incised by corrosion alone because hillslope and confounding processes will induce values of $\bar{u}$, ω, and τ that are above the thresholds necessary for quarrying and abrasion.

The diminishing of sandstone boulders by sculpted forms atop limestone beds raises the question of whether the streams are incising by corrosion or corrosion and abrasion in the associated reaches. As used sensu stricto, bed incision in these reaches does not include pothole and sculpture excavation atop sandstone boulders. However, channel geometry and hydraulics are apparently adjusted to minimize width and maximize ω and τ such that the boulders are diminished in both streams. As a result, channel properties and values of $\bar{u}$, ω, and τ in the Anvil Rock reach are similar to those in the sandstone-bound portion of the Cathole reach and to sandstone-dominated channels elsewhere (e.g., Wohl, 1993). Similarly, values of mechanical incision indices are similar in alluvial reach B to those in reach A, which is incising clastics. By virtue of these observations, abrasion of the sandstone boulders seems to be significant enough to conclude that abrasion is the primary means of channel incision, sensu facto, because significant adjustments are readily discernable in channel geometries and modeled hydraulics.

The results for Greenbrier River and Buckeye Creek suggest that these bedrock streams have adjusted channel geometries and hydraulics to the substrates being incised, but that geomorphic setting has a statistically measurable effect on reach-scale values of ω and τ. Many other variables undoubtedly play a role in determining reach-scale values of ω and τ, but these variables apparently do not collectively overwhelm the effects of substrate and geomorphic setting for the streams at hand because absolute magnitudes of ω and τ scale with substrate resistance (both chemical and mechanical) and geomorphic setting in a logical manner. Notably, the lowest values of ω in both streams are well below the threshold of 200 W m^{-2} proposed for bedrock streams (Tables 3 and 4) (Nanson and Croke, 1992). We hypothesize that this represents a decreased need for mechanical energy expenditure, and hence ω and τ, where corrosion is a significant part of incision. Much of the corrosion may occur during floods of lesser frequency than floods that quarry and abrade insoluble rocks using concussive tools, which raises interesting questions for future research concerning whether formative flood magnitudes are similar for all substrates in bedrock streams.

7. Conclusions

This study is an extension of field-based studies of correlations between reach-scale channel hydraulics and substrate resistance (e.g., Wohl and Ikeda, 1998; Wohl and Merritt, 2001). As with previous studies, numerous variables cannot be controlled. In spite of the resulting potential for uncertainty, tentative evidence is found in Buckeye Creek and Greenbrier River in support of the research hypothesis that bedrock streams can adjust channel geometries and hydraulics to substrate characteristics while maintaining concave profiles (Montgomery and Gran, 2001). For constant geomorphic setting in the Greenbrier River, ω and τ are least atop soluble substrates and ω and τ decline markedly in the downstream direction in Buckeye Creek. The lowest values are found in a cave, where the stream is incising primarily by corrosion. Changes in ω and τ are mediated by changes in channel geometry in Greenbrier River. Channel widths are least atop sandstone and where sandstone boulders clog the channel. The effect of such interactions with hillslopes is that the distributions of ω and τ are not strictly controlled by bed solubility in either stream. For constant substrate solubility along the Greenbrier River, ω and τ are consistently higher where a bedrock cutbank is present or coarse, insoluble sediment enters the channel from valley walls. Coarse, insoluble sediment supplied to reaches in both streams is diminished by abrasion, as evidenced by potholes and smoothing of clast surfaces.

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